Shuttle charging by tether controlled electron beam

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Abstract. During the reflight of the tethered satellite system, the electron generator assembly (EGA) emitted steady electron beams six times with the satellite deployed between 6.2 and 16.1 km. Maximum beam energies and currents were 1.65 keV and 0.4 A, respectively. Data presented here show that: (1) emissions create local electron clouds that can charge the shuttle, (2) ionization of thruster gas by beam electrons in the sheath did not reduce the shuttle potential, (3) the EGA utilizes more than half the induced potential, and (4) ionospheric density gradients and magnetic field orientations affect the circuit’s potential distribution.

Introduction

The Tethered Satellite System (TSS) [Dobrulony and Stone, 1994] consisted of an instrumented, conducting satellite deployed upward from the shuttle by an electrically conducting tether. Orbital motion across the Earth’s magnetic field generated the electromotive force to drive circuit currents. TSS supported three circuit configurations with: (1) one of four resistors connecting the tether to shuttle ground, (2) the fast pulsed electron generator (FPEG) emitting an electron beam, and (3) the tether operating as the electron generator assembly’s (EGA) cathode to emit electron beams. This paper describes ionospheric plasma responses to extended, EGA beam emissions during the deployed phase of the Tethered Satellite System Reflight (TSS 1R). Data are viewed from the perspective of induced ion and electron environments detected by the Shuttle Potential and Return Electron Experiment (SPREE) in the payload bay. We first briefly describe the SPREE, EGA and TSS 1R circuit during EGA operations, then present electron and ion spectral data acquired during six prolonged EGA firings. Detailed analyses are given for two events. The final section discusses coupling of the TSS 1R circuit to the ionosphere.

Instrumentation and the TSS 1R Circuit

The TSS science payload is described in a special issue of Il Nuovo Cimento [1994]. Presented here are measurements of: (1) energetic electron and ion fluxes by SPREE [Oberhardt et al., 1994], (2) currents in the tether by a satellite ammeter [Bonifasi et al., 1994], (3) potential differences between the tether and shuttle ground by a voltmeter in the payload bay [Agénero et al., 1994], and (4) electron densities by a Langmuir probe (LP) on the satellite [Dobrulony et al., 1994].

The SPREE consists of two triqudra spherical electrostatic analyzers (ESAs) mounted on rotary tables. Fluxes of electrons and ions were measured in 32 logarithmically spaced energy channels ranging from 9.8 eV to 10 keV. Particles entered the apertures through angular fans ~100 ø by 8.5 ø, divided into ten zones. Zone 0 looked in the shuttle-horizontal direction and zone 9 looked toward shuttle zenith. Full spectra were compiled simultaneously from all 10 zones and 32 energy steps at a rate of 1 or 8 s -1. Sensor rotation allowed sampling of the 2π sr upper hemisphere every 30 s.

The EGA consisted of two diodes with the tether attached to the cathodes and the shuttle ground to the anodes [Bonifasi et al., 1994]. Current-limited, heater filaments provided the electron clouds from which the beams were extracted. Only one EGA operated at a time and fired directly out of the payload bay. Density measurements were obtained when the LP, ~15 cm from the satellite’s surface, was outside its wake.

Figure 1 is a simplified diagram of the TSS 1R circuit for EGA firings. The satellite at the tether’s high potential end collected ionospheric electrons, allowing current to flow through the tether. With the EGA operating, an electron beam nearly equal to the tether in current was emitted into the ionosphere. Preflight testing showed that leakage currents to the anode were negligible. The energy of emitted electrons equaled the potential difference applied between the cathode and anode and was measured by the voltmeter. In this configuration, the shuttle ground was isolated from the circuit and the shuttle potential, ΨS, floated with respect to the ambient plasma. If the trajectories of energetic, EGA-generated electrons returned to the shuttle, ΨS as-
sumed the negative values required to attract an equal number of cold ions from the ionosphere to its grounded conducting surfaces. When the circuit was open the satellite and shuttle were very near their local plasma potentials, and the voltmeter essentially measured the entire motionally induced potential, \( \Phi_0 = (V_S \times B) \cdot L \), where \( V_S \) is the shuttle velocity, \( B \) the magnetic field, and \( L \) a vector along the tether.

**Observations**

Data in Table 1 describe the six prolonged EGA beam emissions of the TSS 1R deployment which occurred in two predefined sequences. The first two events lasted 56 s and the last four 224 s. Table 1 lists the universal time, UT, on February 26 or 27, 1996, when each firing began, local time, LT, tether length, \( L \) (kilometers), tether current, \( I_T \) (milliamps), shuttle potential, \( \Phi_s \), open-circuit potential, \( \Phi_0 \), potential applied to the EGA, \( V_{1,2} \), potential drop along the tether, \( R_T I_T \), satellite potential, \( \Phi_{sa} \), plasma density, \( n_e \) (cm\(^{-3}\)), and beam pitch angle, \( \alpha_B \). Cited values of \( \Phi_0 \) and \( I_T \) were taken near the beginning and end of each beam emission. Potentials are given in volts. Values of \( \Phi_{sa} \) were estimated using Ohm's law,

\[
\Phi_0 = V_{1,2} + R_T I_T + \Phi_{sa} - \Phi_S
\]  

(1)

The tether resistance \( R_T \approx 1.8 \, \text{k} \Omega \) [Chang et al., 1997]. The EGA perveance, estimated from simultaneously measured values of \( V_{1,2} \) and \( I_T \) was very close to its prefight specification of 6.4 \( \mu\text{P} \).

The data in Table 1 demonstrate three points: (1) The shuttle was in sunlight for five of the emissions; event 4 occurred as the shuttle crossed the dusk terminator. (2) Except for event 4, values of \( V_{1,2} \) and \( I_T \) remained narrowly confined during individual EGA emissions. (3) Values of \( \alpha_B \) indicate that the beam had strong field-aligned components in three events and should have escaped the shuttle. During the two 56 s and the last 224 s emission, beam electrons were emitted almost perpendicular to \( B \). A large fraction of them should have returned to the shuttle [Hardy et al., 1995]. The most strongly negative shuttle potentials occurred during the \( \alpha_B \approx 90^\circ \) emissions.

Plate 1 gives the directional differential fluxes of electrons (top plot) and ions (lower plot) measured by SPREE during the four 224 s firings. Plate 1A shows that SPREE detected intense fluxes of electrons with nearly thermal shapes. Flux modulations in this spectrogram reflect gradients in the densities of electron guiding centers sampled as SPREE rotated. The maximum electron fluxes, \( \approx 5 \times 10^{11} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \), were detected as SPREE faced shuttle-forward. The local densities of superthermal electrons were \( >10^3 \text{ cm}^{-3} \). Ion fluxes were confined to the lowest energy channel of SPREE, indicating that \( \Phi_S > -10 \, \text{V} \). During subsequent events, electron fluxes were detected at lower energies even though the emitted beams were more energetic and carried larger currents.

Data in Plate 1B suggest that the shuttle passed through a transition region. At the beginning of the event, electron spectra were similar to those of Plate 1A. Thereafter, electron fluxes decreased and ion fluxes rose. The progression of the ion spectral peak indicates that the shuttle charged to increasingly negative potentials. Figure 2 presents detailed measurements from this 4 min interval. Figure 2a shows values of \( V_{1,2} \) (open circles) and \( I_T \) (closed circles). The dashed line represents the total potential induced in the circuit estimated by a linear extrapolation between measurements of \( \Phi_0 \) taken just before and after the EGA fired. Note that tether length increased, the shuttle's speed was constant, and the magnetic field decreased. In fact, all three quantities \( \Phi_0 \), \( V_{1,2} \), and \( I_T \) decreased with time. Figure 2b plots the tether potential drop \( R_T I_T \), \( \Phi_{sa} \), and \( \Phi_{sa} \) determined from (1) and the SPREE data as a function of UT. \( \Phi_{sa} \) values estimated from Ohm's law substantially agree with measurements made on the satellite [Stone et al., 1994].

**Figure 2.** Measurements acquired during the EGA firing at 2359:58 UT. Data in the left and upper right plots are explained in the text. The lower right plot qualitatively represents magnetically limited current-voltage characteristics of the satellite in three electron ambient plasma density environments.
Plate 1. SPREE differential electron (top) and ion (bottom) fluxes for the four 224 s EGA firings. Plots A, B, C, and D correspond to events 3, 4, 5, and 6 in Table 1. The initial UT is given, with tick marks at one minute separations.

Figure 2c shows that during the shuttle charging transition $I_T$ decreased as $\Phi_{SA}$ rose. Under steady density conditions a magnetically limited current-voltage relationship maintains [Stone and Bonifazi, 1997]. Langmuir probe measurements on the satellite indicate that plasma density fell from $\sim 1.3 \times 10^6$ cm$^{-3}$ at 2358 UT to $\sim 1.8 \times 10^5$ cm$^{-3}$ at 0004 UT. Reliable density measurements could be made only when the probe faced the satellite ram direction and beam systems were inactive. Figure 2d offers a schematic of the current-voltage characteristics for positively charged satellites with three different, but constant, external ionospheric densities [Stone and Bonifazi, 1997]. The arrow indicates that if plasma density fell rapidly, the $I_T$ versus $\Phi_{SA}$ shown in Figure 2c is qualitatively intelligible.

Ionic spectra acquired during the two 56 s EGA firings (Plate 2) resemble those in Plate 1D except that after an initial transient, $\Phi_S$ remained steady at $\sim 90$ V. This highest level of shuttle charging during EGA firings was achieved at relatively short tether lengths and low tether currents (Table 1). At $\sim 2317:23$ UT two aft vernier thrusters fired and $\Phi_S$ rapidly changed from -90 to $\sim 120$ V, then returned to its pre-firing value. During the $\sim 6$ s interval between the thruster firing and EGA turn off, SPREE detected intense ion fluxes in all energy channels up to 90 eV. This indicates that secondary ionization was generated inside the potential sheath around the shuttle. Intermediate energies reflect potential differences between the shuttle and the birth locations of new ions. The two thrusters which caused the enhanced shuttle potential and sheath ionization are directed downward and splash gas off the shuttle wings. During TSS 1, firings of these thrusters consistently increased potential differences between the shuttle and the ionospheric plasma [Machuzak et al., 1996]. On TSS 1R, with resistors in the circuit, SPREE detected similar increases in the magnitude of $\Phi_S$ during firings of these thrusters [Gentile et al., 1997], but no significant ion fluxes appeared at energies below the charging peak. It was thus concluded that incoming ions with energies $\lesssim 600$ eV produced little new ionization in crossing the sheath. At the time of the thruster firing, the EGA was emitting an electron current of 130 mA at an energy of 795 eV (Table 1). These electrons traverse the shuttle's sheath with kinetic energies sufficient to ionize a measurable fraction of neutrals in the near-shuttle plume. Since $\Phi_S$ became more negative, neutrals in the plume were more effective at inhibiting ambient ions from reaching the shuttle's conducting surfaces than beam electrons were in increasing sheath ionization.

Discussion

The discussion of Figure 1 argues that during EGA firings the shuttle was isolated from the TSS 1R circuit and $\Phi_S$ floated with respect to the ionospheric plasma. To intercept equal fluxes of ions and more mobile electrons, spacecraft in the ionosphere normally float at a few tenths of a volt negative. $\Phi_S$ readings of several tens of volts require the local presence of dense superthermal electrons. Only electrons with energies sufficient to overcome the $\Phi_S$ barrier reach shuttle conducting surfaces. Floating values of $\Phi_S$ depend on the ambient plasma density, the energy/density of the superthermal electron population and the magnetic field direction. Data in Plate 1B and Figure 2 clearly demonstrate the role of the background plasma density.

Control by the magnetic field is seen empirically. The
largest values of $|\Psi_s|$ occurred when $\alpha_B$ was $\sim 90^\circ$. In all three cases the magnetic field was mostly in the shuttle-horizontal plane, pointing aft of the right wing. As beam electrons emerged from the EGA they experienced magnetic forces that turned them back toward the shuttle, aft of the TSSpayload. In the other three EGA firings the beam was more magnetically aligned and could escape the shuttle easily. Although electron fluxes reaching SPREE were intense, their energies were substantially below that of the beam ($V_{i,2}$). Thus, most of the electrons reaching SPREE were heated ambient and secondaries created in collisions with neutrals. When the beam was magnetically bent in the shuttle-aft direction, the access of warm electrons, and perhaps even beam electrons, to current-collimating surfaces was increased, driving $\Phi_S$ more negative.

During the six events, the EGAs emitted sustained electron beams with energies and currents up to 1650 eV and 400 mA. The efficiency of the TSS 1R circuit can be assessed by examining the distribution of potentials in Table 1. The potential from orbital motion, $\Phi_0$, is distributed throughout the circuit according to Ohm's law. On average, more than half of the potential ($V_{i,2}/\Phi_0$) was available for electron beam firings. About 30% of the potential ($\Phi_{sa}/\Phi_0$) was required to support the extraction of electrons from the ionosphere by the satellite; $\sim 17\%$ was dissipated in the tether ($R_T I_T/\Phi_0$). Thus, only a small fraction ($\Phi_S/\Phi_0$) could be allocated to the shuttle's sheath.

Table 1. TSS Circuit Parameters during EGA Firings

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